Basics of Wind Diesel Power Systems

September 28th, 2004

Ian Baring-Gould
NREL

Session Overview

- Provide an overview of power system design and configurations
- Describe renewable power penetration and the basic design of wind/diesel power systems
- Review common power system components and their purpose
- Discuss power quality issues of wind diesel power systems
- Introduce the role of storage

Session Goals

Provide people who are new to wind diesel power system technology with a basic understanding of these new power system options

Key Messages

Wind diesel power systems are an economic reality that can be used to limit or reduce the dependence on diesel fuel however they are complex and require some understanding of different power system components and systems.

History of Wind/Diesel

- Research stated in earnest in the late 1970's as a result of the first oil crises
- Many installations in the early 1980's,
  - Primarily in Europe associated with research laboratories
  - Example systems in Alaska
  - Smaller systems with single diesels
- Component and modeling work initiated in the late 1980's - focus on test platforms and control
- Early 90's saw a reduction in research activities, though many advances made in control theory
- Growing popularity for rural electrification has resulted in a technology resurgence in late 1990's

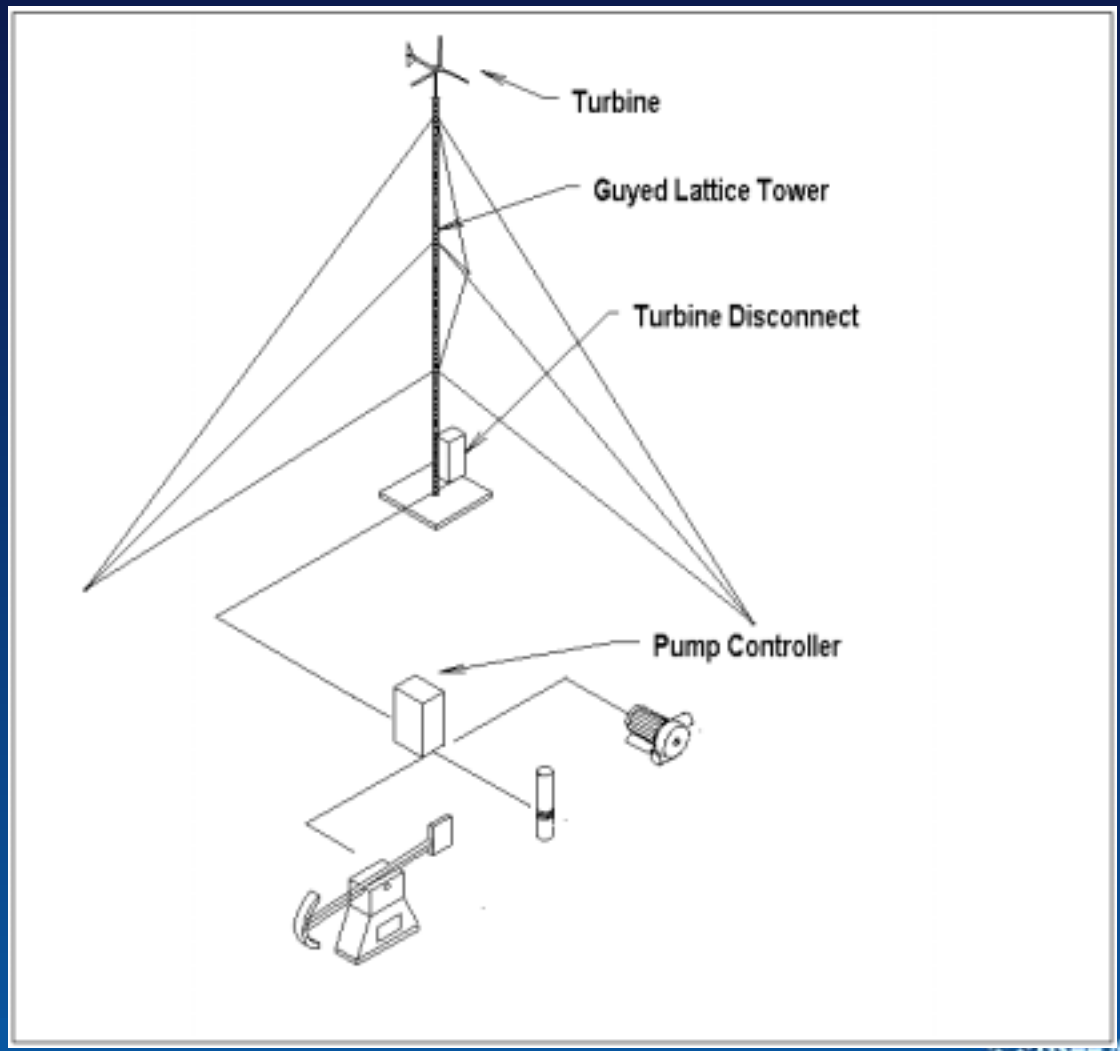
Stages of Remote Power Systems

Renewable power system can be used to cover a wide range of needs.

These include:

- **Dedicated use:** Water pumping/ice making.
- **House systems:** Power systems for individual buildings, dispersed generation.
- **Community Power Systems:** Power provided to a large community with large loads
- **Wind/Diesel Systems:** Large communities with large loads

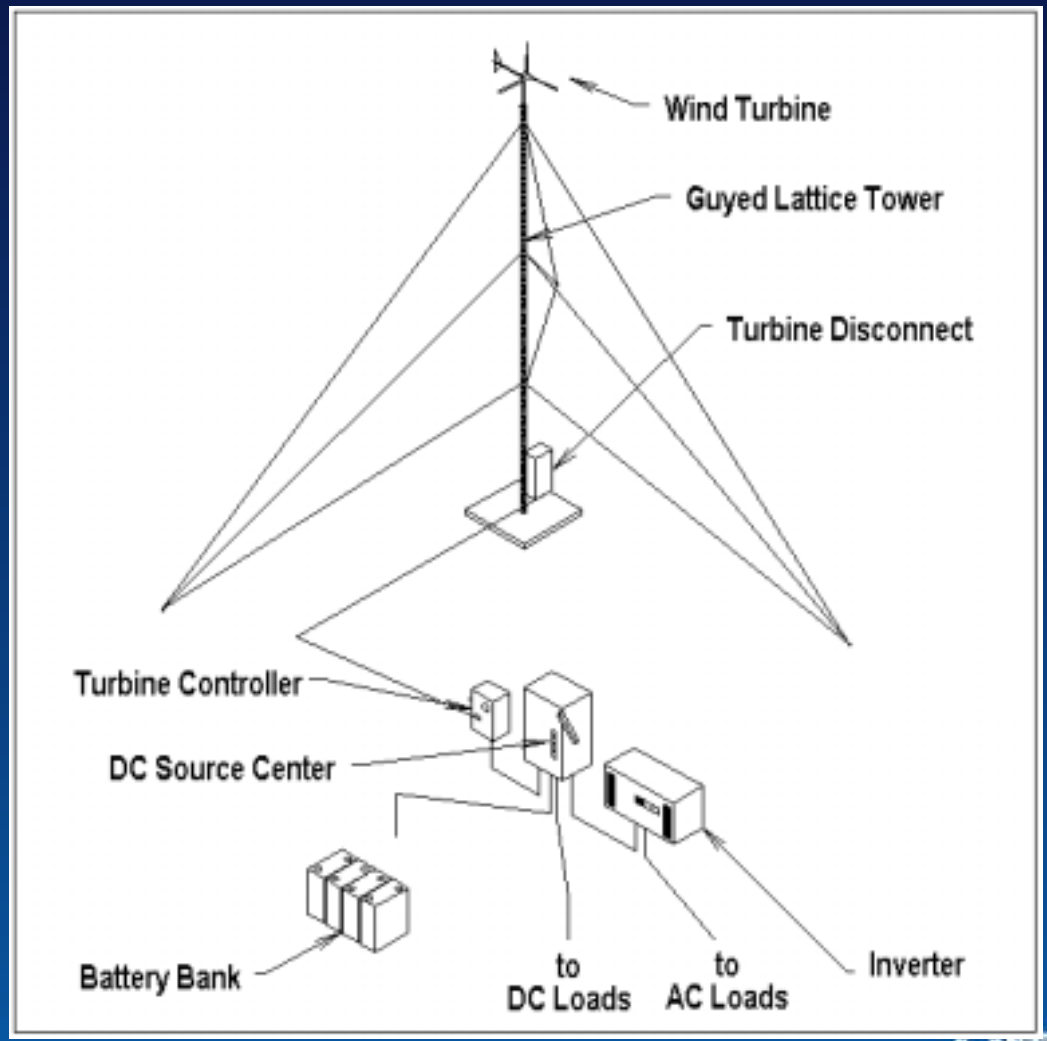
Direct connect Water Pumping



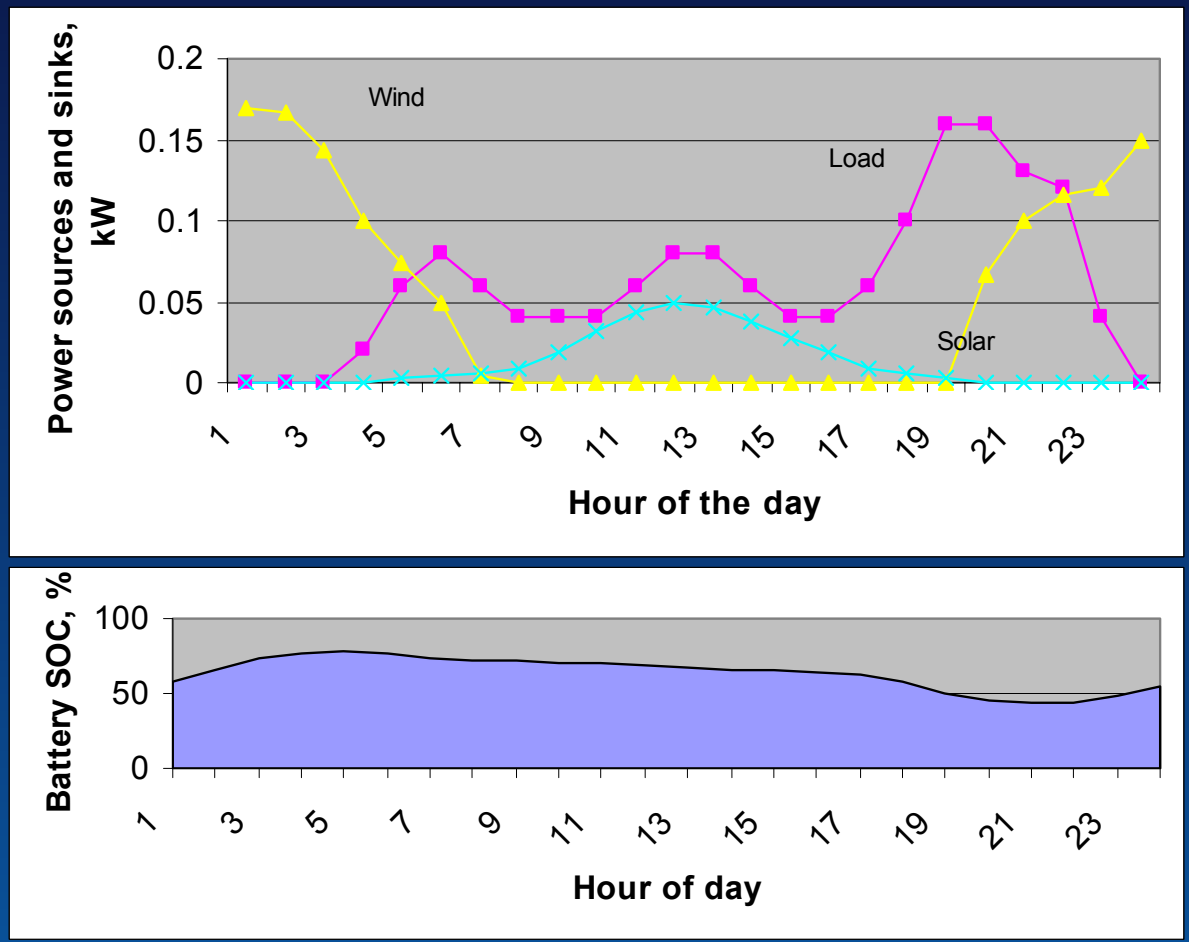
Small Power Systems

- Systems do not have a dispatchable backup generator like most hybrids
- Very simple architecture:
  - Turbine, PV, Disconnects, Batteries
  - DC Loads or AC power through an inverter
- Primarily PV dominated for small loads, wind has potential at larger loads.
- In many instances a combination of PV and wind make most sense
- Can vary in size, power output

Single Source System Architecture



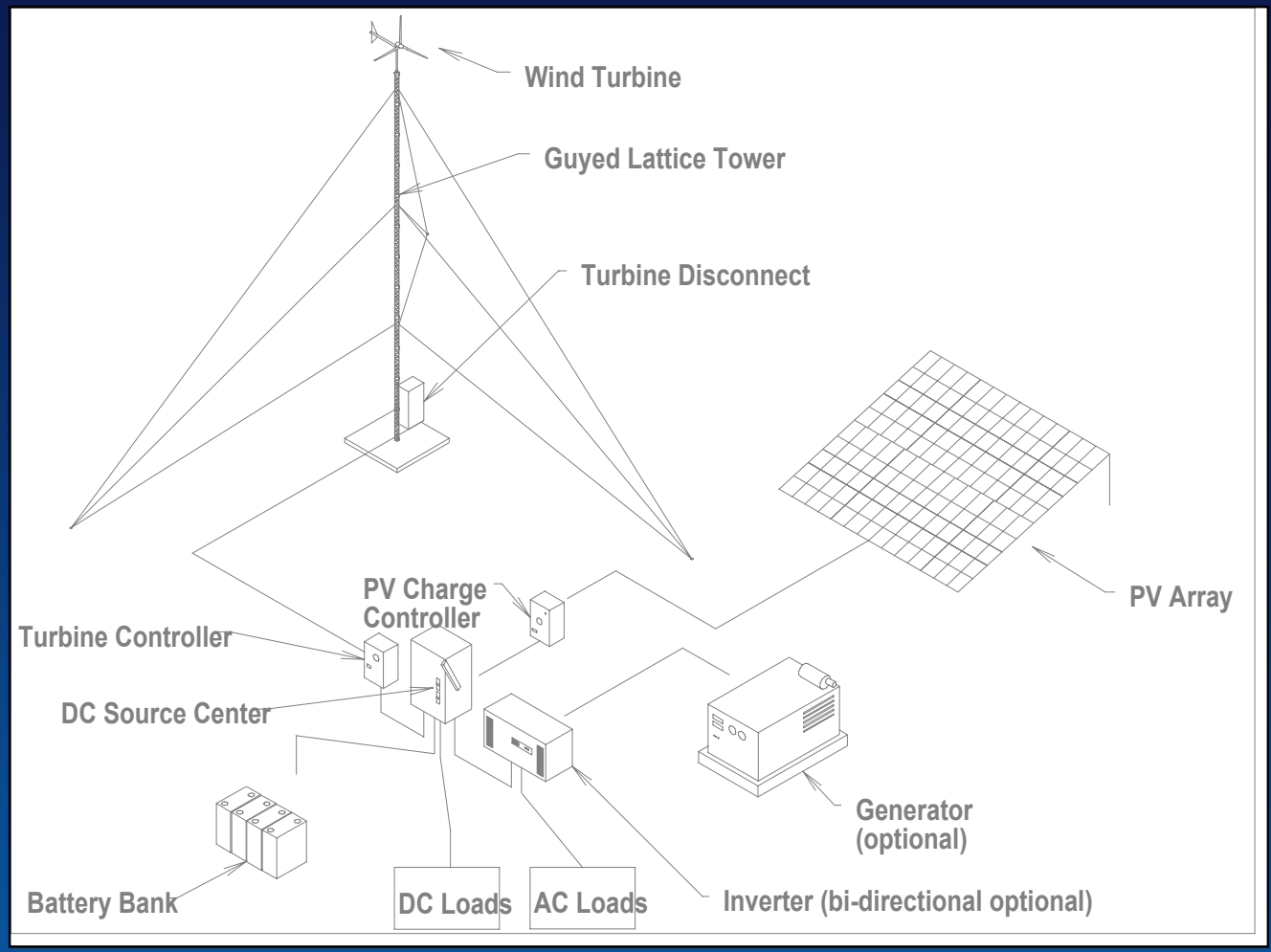
Energy Flow for a Small Hybrid



Village Scale Power Systems

- Larger, village scale power systems use centrally located power plants and distribute AC power to the connected homes.
- Single point of service and maintenance
- Usually use larger or multiple generation units to improve operation performance and benefit from quantities of scale benefits
- Act very much like small power utilities
- Provide “grid” style power

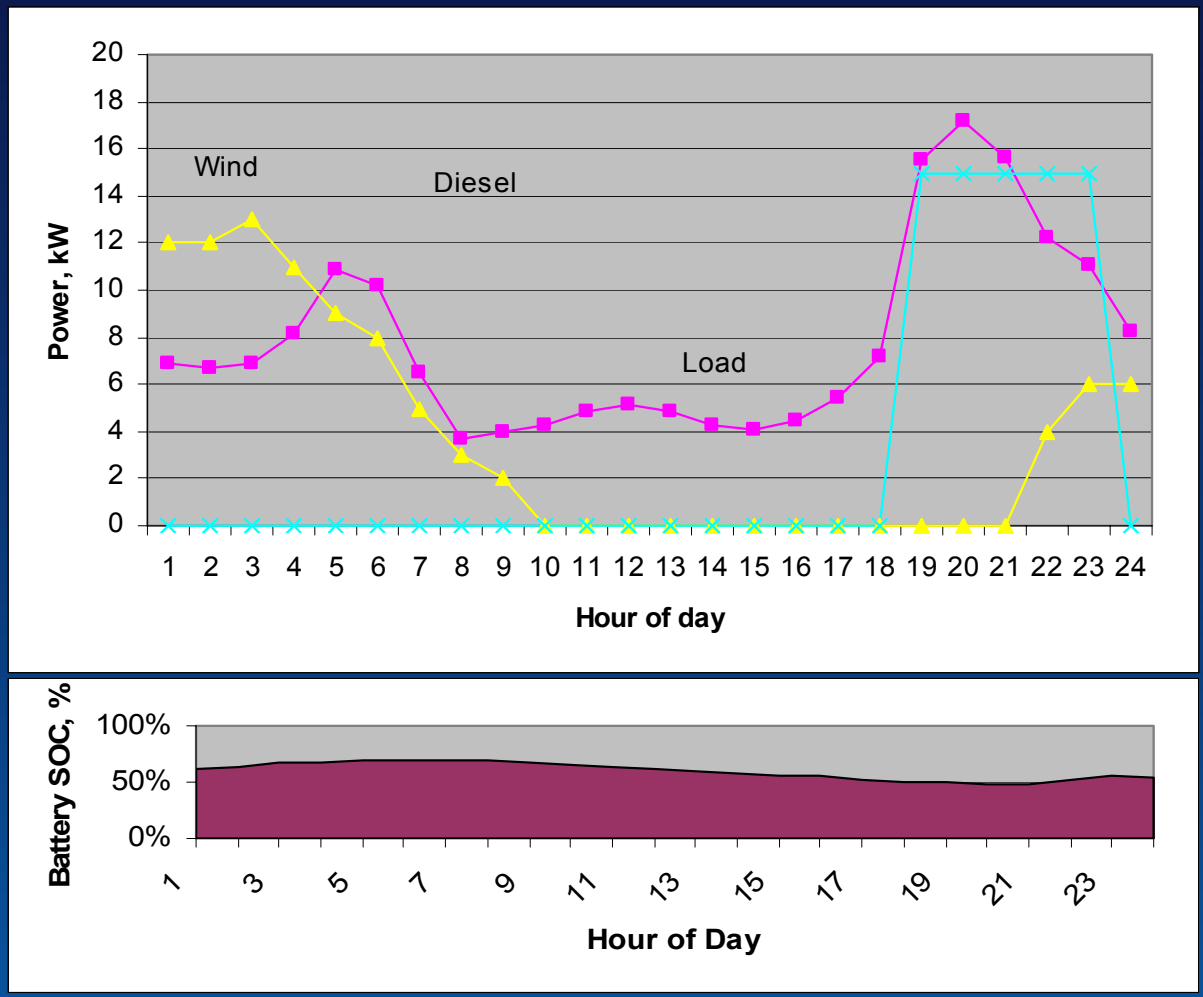
Village System Architecture (DC)



Micro-Grid Power Systems

- Supply communities with demands from ~100kWh/day load (15 kW peak load) up to ~700 kWh/day (75 kW Peak load)
- Components of wind, PV, biomass, batteries and conventional generators
- Generally provide AC
- Use of batteries to store renewable energy for use at night or low renewable times
- Generator used as backup power supply
- Mature market

Parallel System



Both diesel and inverter needed to cover the maximum load.

Both units run together.

Wind-Diesel Power Systems

- Larger systems with demands over ~ 100 kW peak load us to many MW
- Based on an AC bus configurations
- Batteries, if used, store power to cover short lulls in wind power
- Both small and large renewable penetration designs available
- Large potential mature with fewer examples
- Due to cost - PV generally not used

Penetration

Instantaneous Penetration:

$$\text{Instantaneous Penetration} = \frac{\text{Wind Power Output (kW)}}{\text{Primary Electrical Load (kW)}}$$

- Voltage and frequency control
- Reactive power

Average Penetration: (generally a month or a year)

$$\text{Average Penetration} = \frac{\text{Wind Energy Produced (kWh)}}{\text{Primary Energy Demand (kWh)}}$$

- Total energy savings
- Loading on the diesel engines
- Spinning reserve losses/efficiencies

AC Based Hybrid System

- **Low penetration systems -** Wind acts as a negative load, very little control or integration of wind turbines into the power system is needed .
- **Mid penetration systems -** Wind becomes a major part of the power system. Additional components and limited automated control is required to insure that power quality is maintained. Little operational control required though may be used.
- **High penetration systems -** Completely integrated power system with advanced control. Limited operational control of system by plant staff

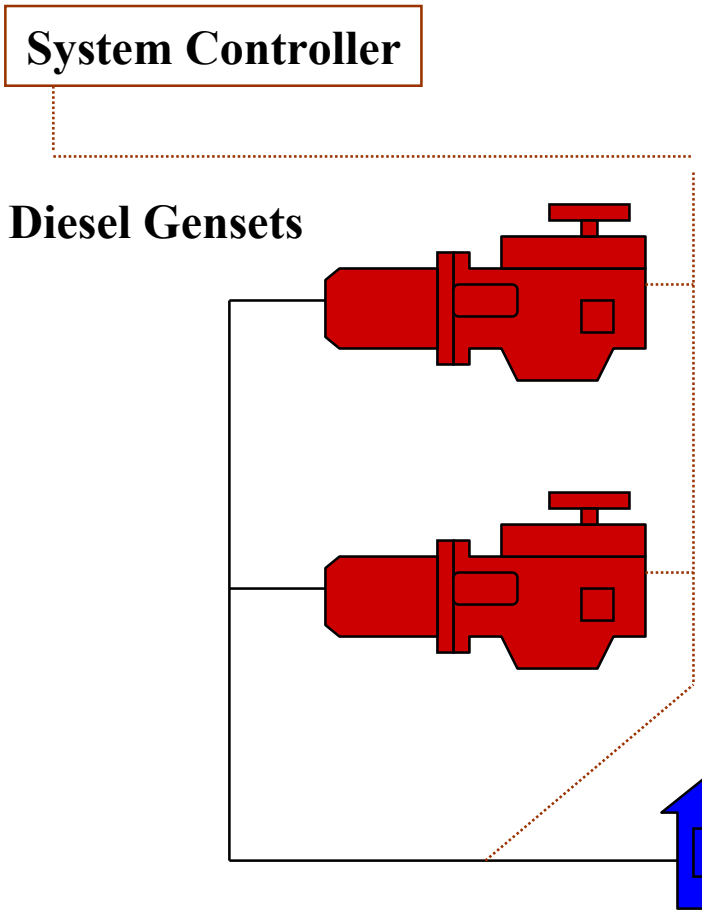
System Penetration

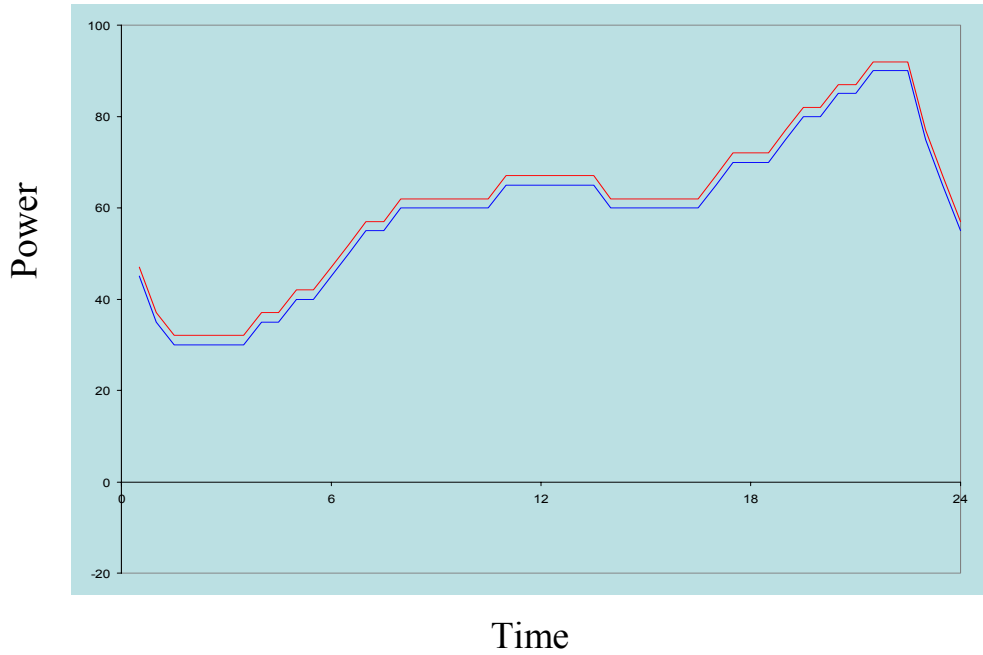
	Low	Medium	High
Peak Instantaneous	<50%	50 – 100%	100 – 400%
Annual Average	<20	20 – 50%	50 – 150 %
Commercial status	Fully utilized	Well proven Fully commercial Multiple use	System prototype Operating
Examples	Denmark, Greece	San Clemente, CA Kotzebue, Ak Coyaique, Chile	St. Paul Wales Ak

These are really three different systems which all should be considered differently

Note: People play loose with the definitions

Diesel Only Power System



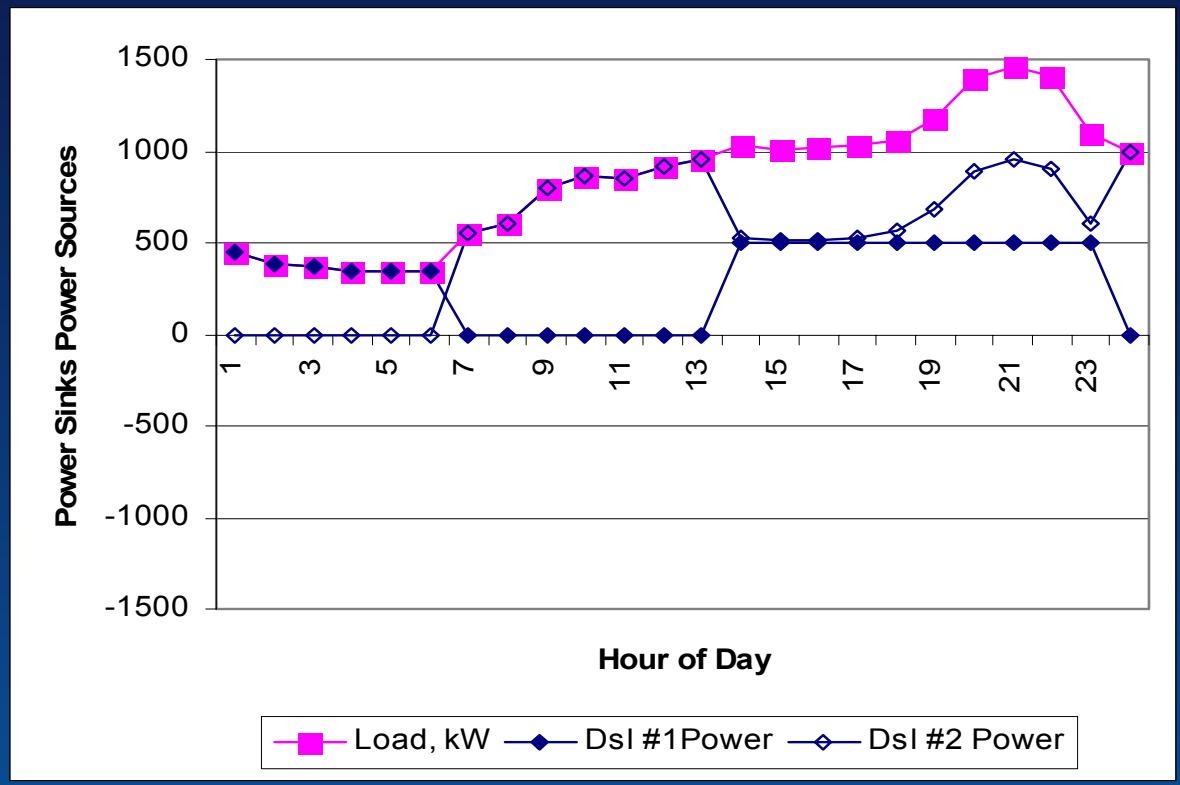


Multiple diesel plants with control

In multiple diesel systems the diesels may be dispatched to take advantage of size and load.

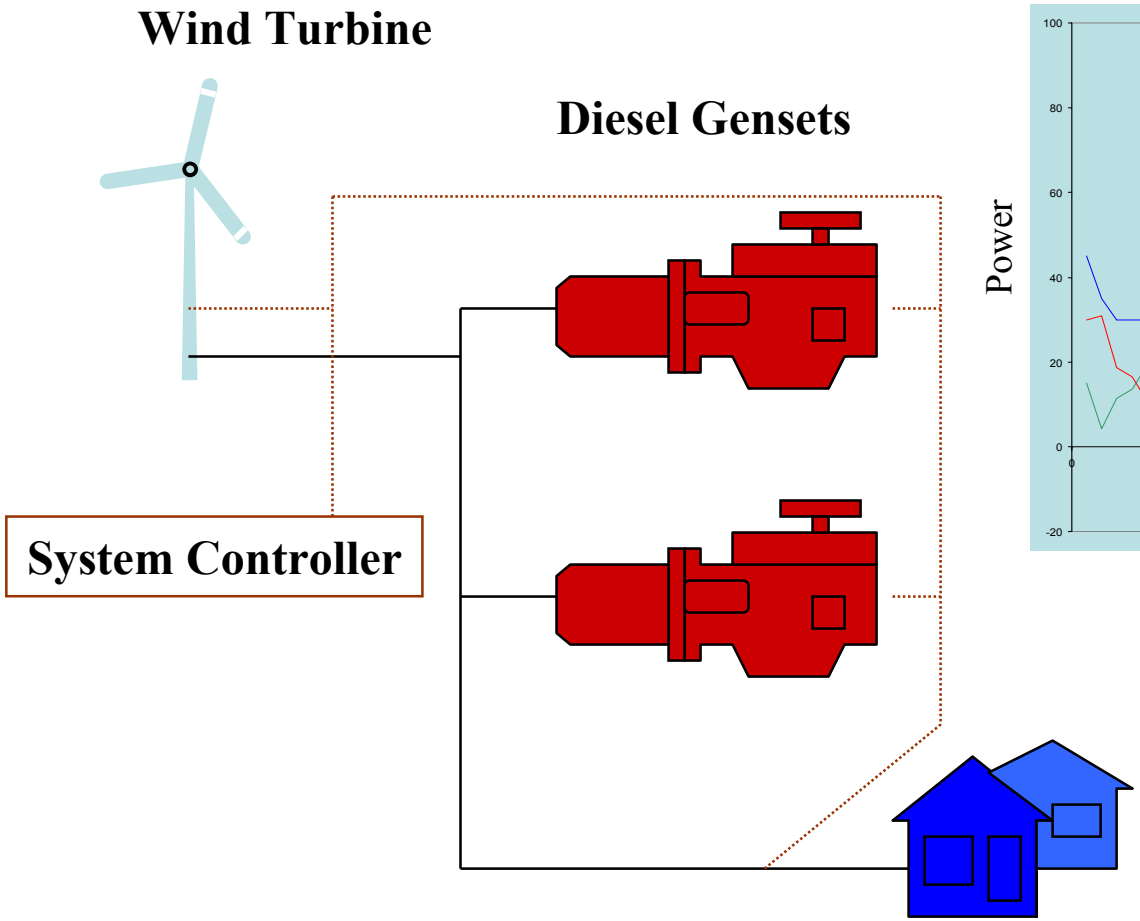
Generally requires automatic diesel control.

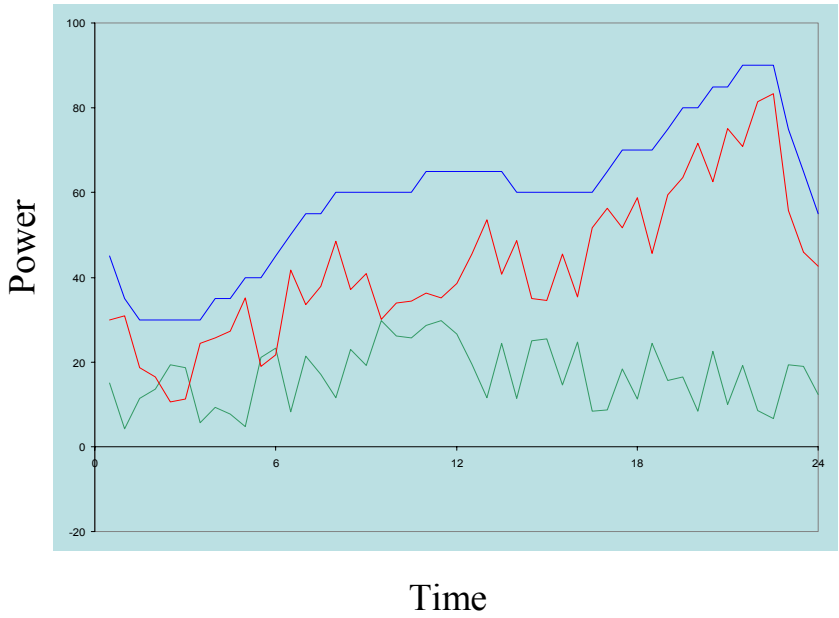
Favorable in power systems with renewables



Potential use of a 500 and 1000 kW diesels

Low Penetration wind/diesel system

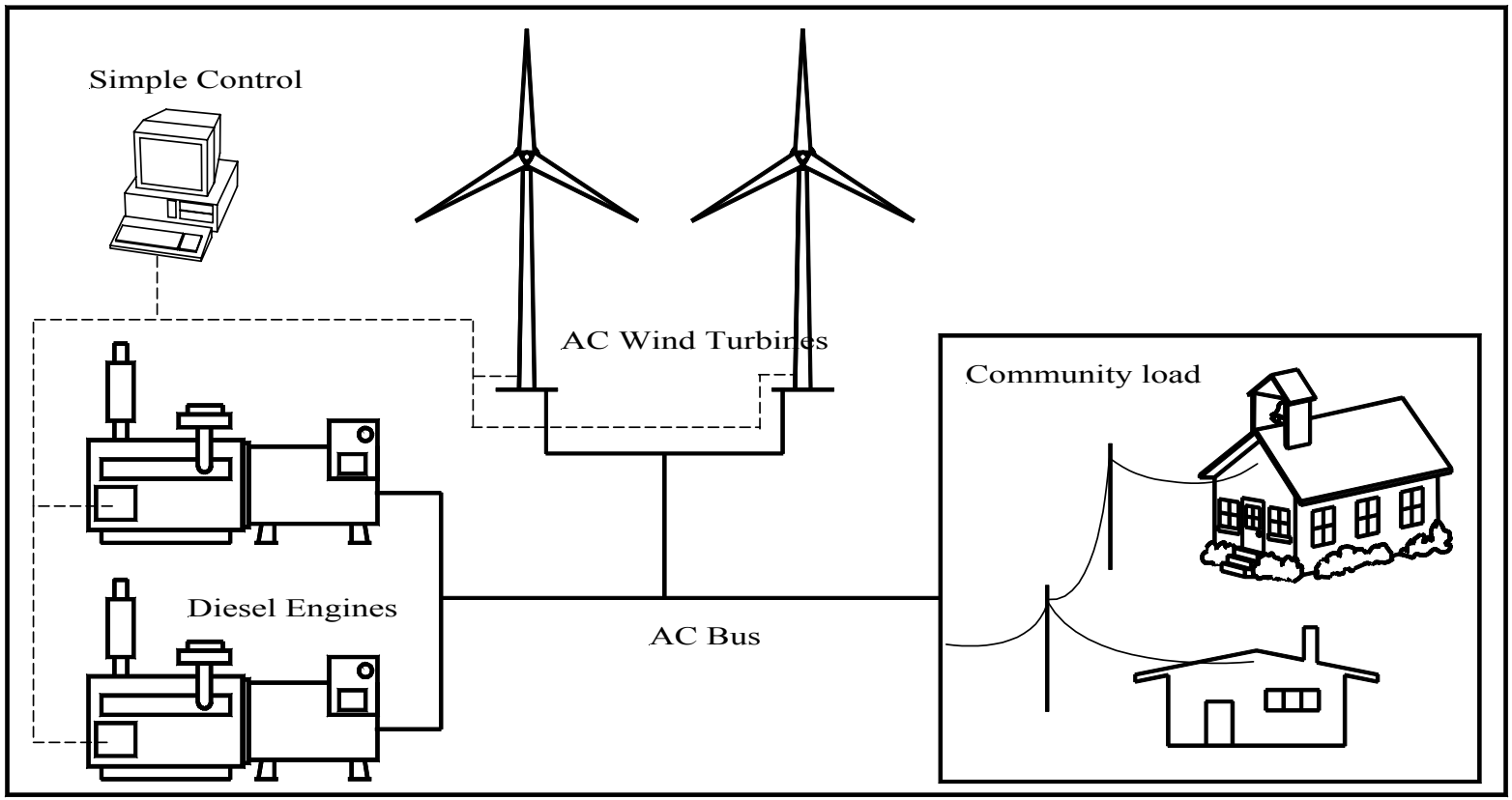




Low Penetration W/D Specifications

- Equipment
  - Wind turbine or series of turbines
  - Dump load could be include to smooth out power fluctuations
  - Capacitor bank used correct power factor if needed
- Control
  - Wind turbine monitoring
  - Power control of wind turbines possible but not required
  - Minor controls to allow remote turbine shut down in extreme cases

Low Penetration W/D Schematic



Low Penetration W/D Principles

- Wind acts as a negative load on diesels and thus reduced diesel fuel consumption
- If lead diesel has new linear controls - diesel simply adjusts power to supply difference
- In high peak wind periods, primary diesel runs at low loading, inefficient but saves diesel fuel
- Diesels may operate outside of their “standard” operating region, not critical but may require more maintenance
- Some control may be placed on the wind turbines to limit the power generation during times of low loading

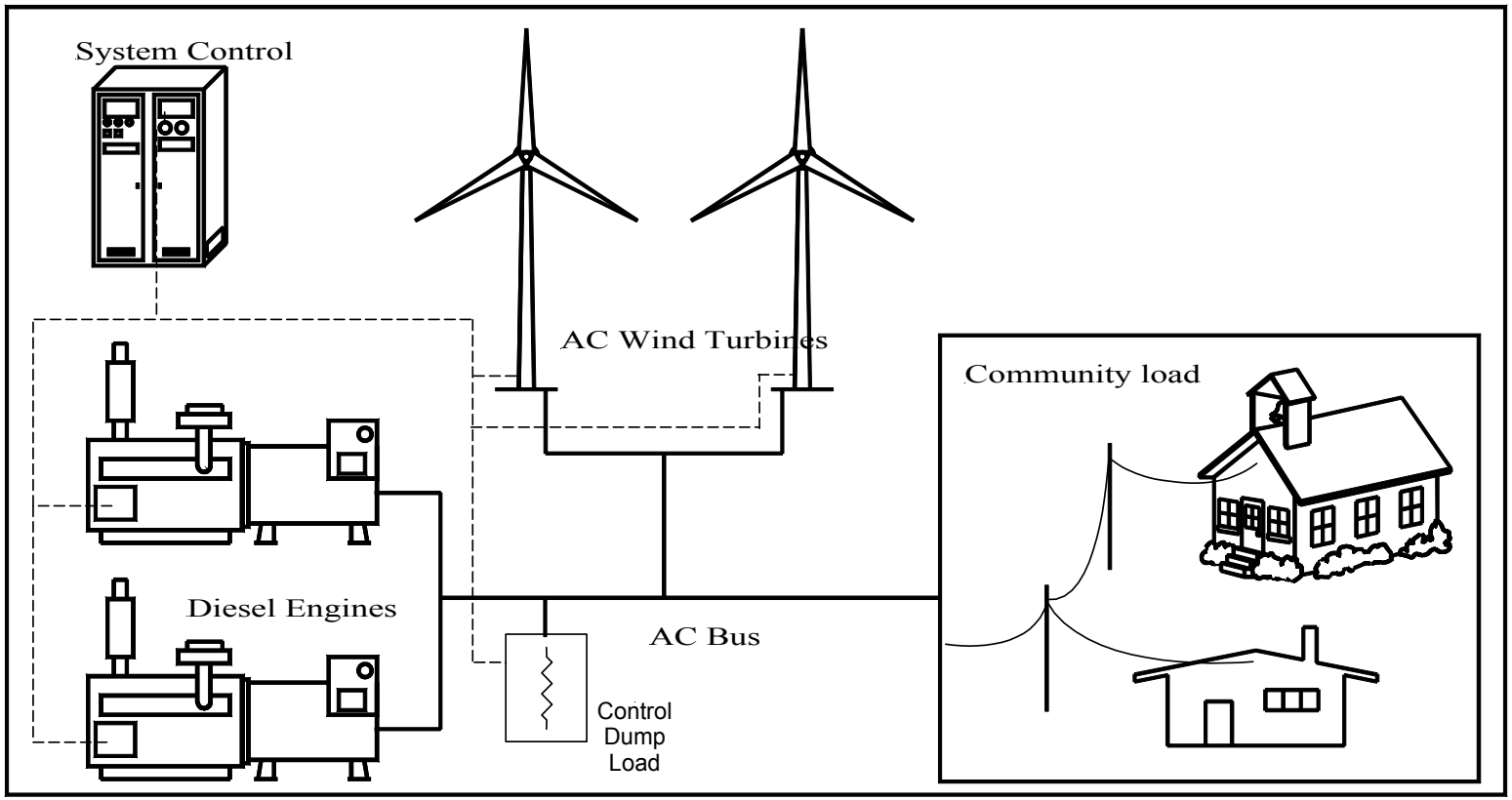
Low Penetration

- Capital cost of between $1,000-1,500/ per kW of wind capacity, excluding diesel units and plant BOS
- Easy integration with existing diesel system, little or no diesel modifications required
- Modest fuel savings of up to ~20% possible.
- System support requirements:
  - Wind turbine maintenance.

Medium Pen W/D Specifications

- Equipment
  - Wind turbine or series of turbines
  - Dump load to smooth out power fluctuations
  - Dispatchable loads to reduce loading on diesels and help control system frequency - May have capacitor bank
- Control
  - Wind turbine controls
  - Power control of wind turbines possible but not required
  - Diesel control
  - System controller to maintain system stability and dispatch primary diesels and wind turbines as needed
  - Some power forecasting may be implemented

Medium Penetration W/D Schematic



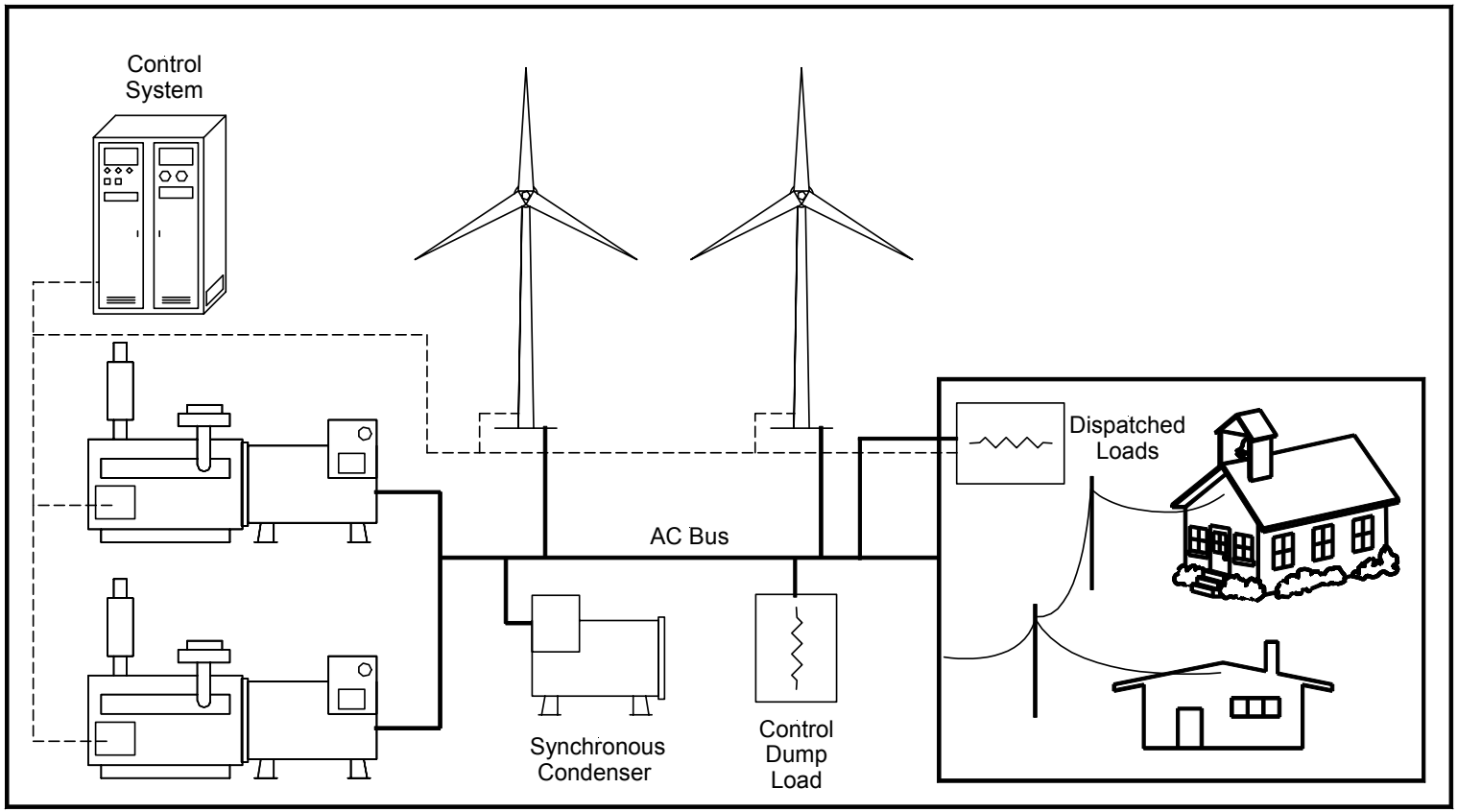
Medium Pen W/D Principles

- Wind acts as a negative load on diesels
- Lead diesel have advanced control capabilities - diesel simply adjusts power to supply difference
- Secondary diesels may be shut off when not needed, reduces diesel operating hours
- Diesel expected to operate at all times
- In high peak wind periods, primary diesel runs at low loading and/or dump load used to set minimum loading
- Diesels will operate outside of their “standard” operating region, not critical but may require more maintenance

High Pen W/D Specifications

- Choice # 1: No Storage systems
- Equipment
  - Wind turbine or series of turbines
  - Dump load to smooth out power fluctuations
  - Synchronous condenser to allow autonomous operation
  - Dispatchable loads to reduce loading on diesels and help control system frequency - May have capacitor bank
- Control
  - Wind turbine and advanced diesel controls
  - Power control of wind turbines possible but not required
  - Fully integrated system controller
  - Some power forecasting may be implemented

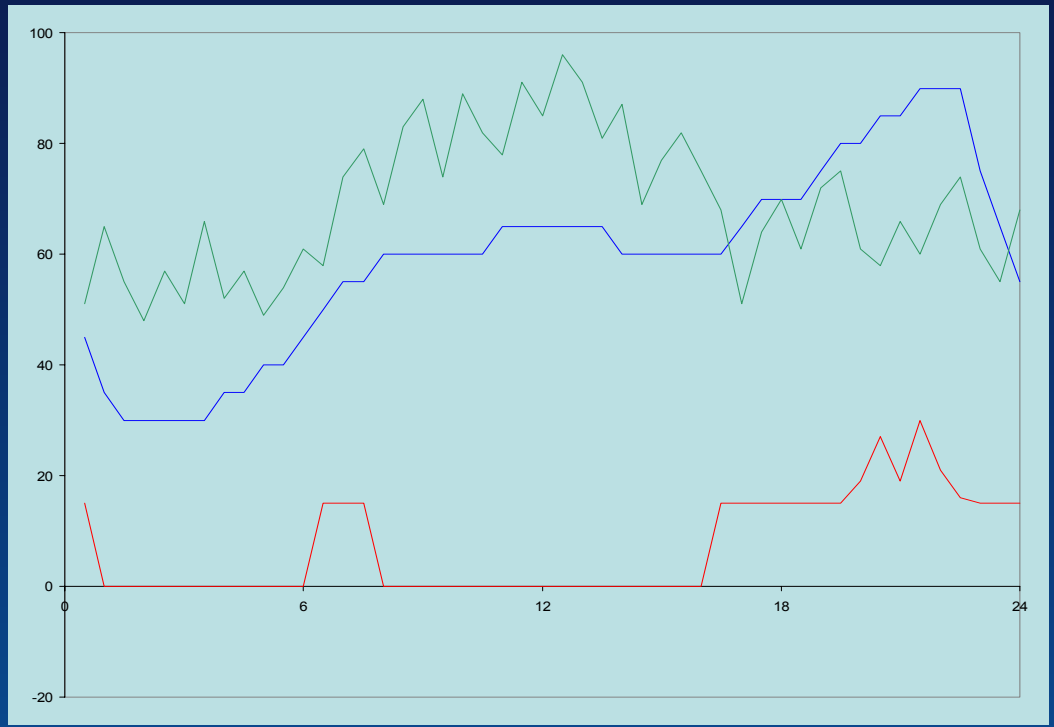
High Penetration W/D Schematic



Wind Diesel without Storage

When the wind power is larger than the load by some margin - Diesel is shut off.

- Frequency controlled by dump load
- Voltage controlled by condenser

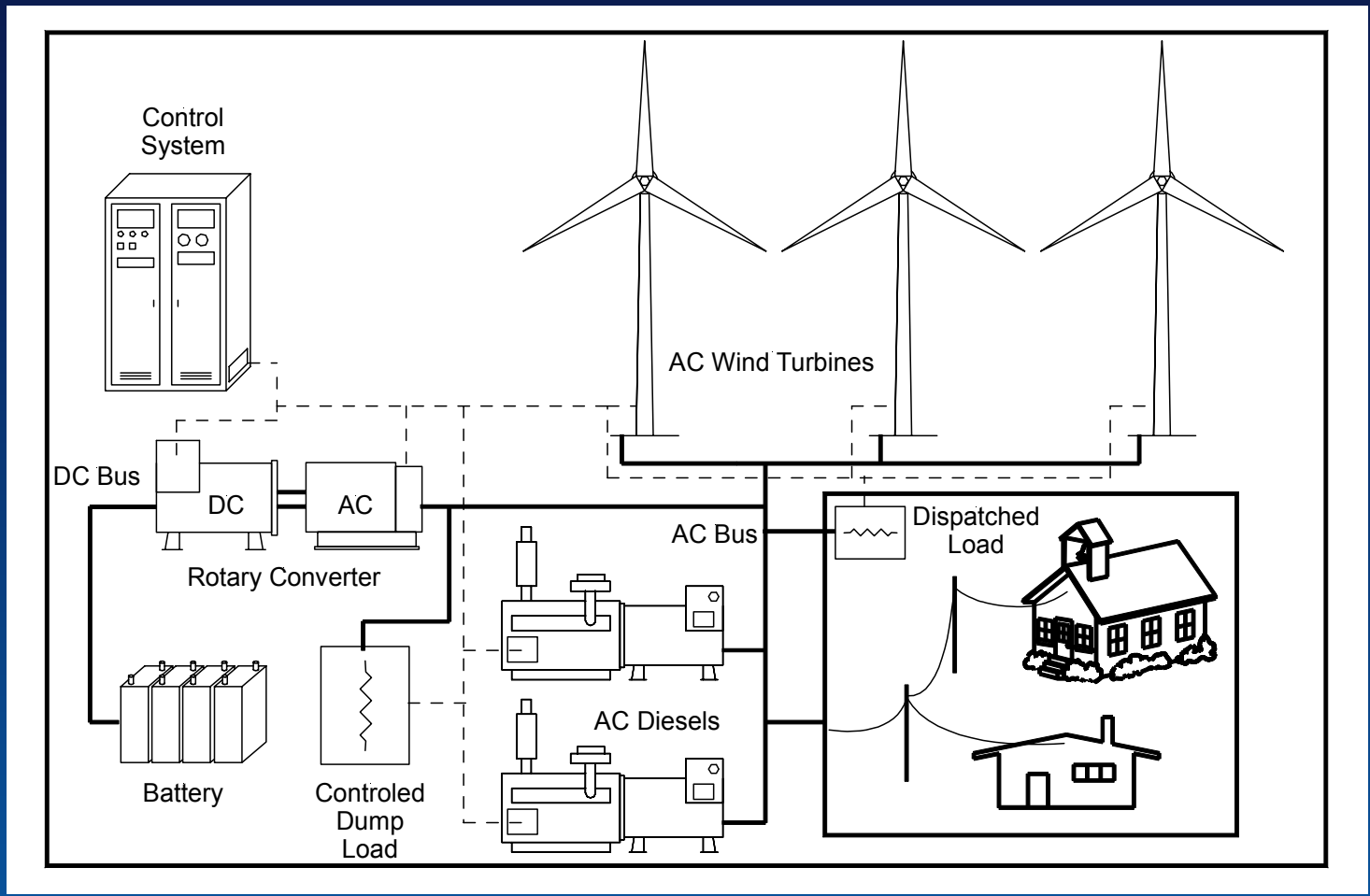


Red = Diesel
Blue = Load
Green = Windpower

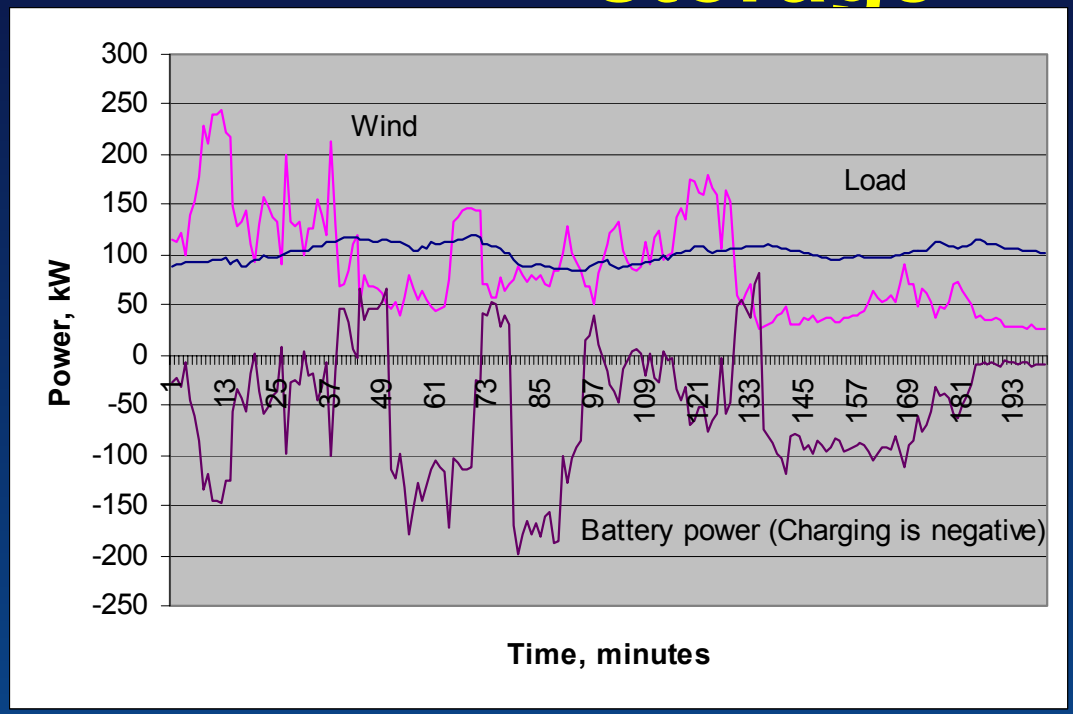
High Pen W/D Specifications

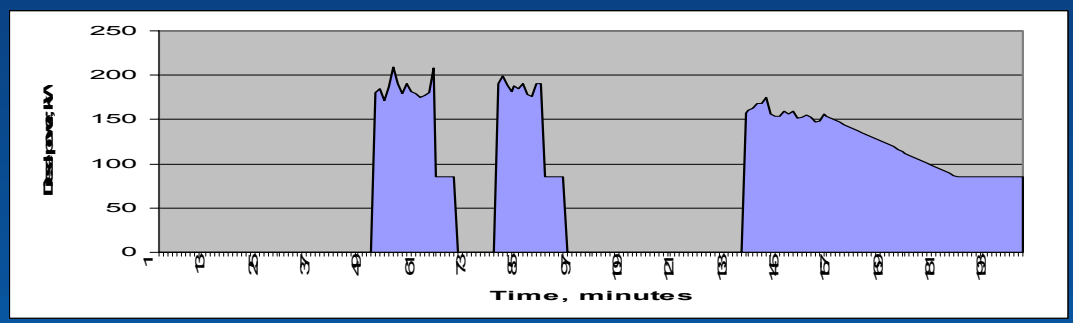
- Choice # 2: Storage systems
- Equipment
  - Wind turbine or series of turbines
  - Dump load to smooth out power fluctuations
  - Power converter and battery with ability to provide power control
  - Dispatchable loads to reduce loading on diesels and help control system frequency - May have capacitor bank
- Control
  - Wind turbine and advanced diesel controls
  - Power control of wind turbines possible but not required
  - Fully integrated system controller
  - Some power forecasting may be implemented

High Penetration W/D Schematic



Wind/Diesel with short term storage





- Diesel used to provide power to system when the wind can not cover load.
- Battery used to fill short gaps in or to start diesel

High Penetration W/D Principles

- Use of wind allows all diesel engines to shut down, reducing fuel consumption and operation hours
- System controller continually monitors power system and dispatched equipment as needed to maintain system integrity
- During mid to high wind periods, all diesels shut off
- Very technology dependent system architecture that required automated operation
- Should include a fail safe operation strategy

Systems and Components

- Hybrid power systems are made up of separate pieces of equipment that are brought together to form a cohesive power system
- Configuration and component size depend on the load and resource available at site
- Controlling the power systems is a complicated question, both logically and technically.
- Must understand the components

Dispatchable Generators

- Generators that can be turned on with short notice.
  - Diesel, Gas, Natural Gas, Bio-gas
- Usually require a lot of maintenance
- Role depends on system design.
- Wide range of old and new technology
- Wide range of control

40 kW Diesel Generator

Wind Turbines for Hybrids

- Range in size from 300W to 750kW
- Large turbines with diesel plants
- Small turbines designed for remote applications
- inst cost $1 - $4 per W
- Cost as low as $0.04 / kWh produced

Photovoltaics

- Applicable for small, remote applications
- Installation cost of ~$10/W, LCC of $0.22/kWh
- Low maintenance requirements
- Quite accepted internationally
- Not used commonly in large applications but there are some examples

PV on Active Tracker

Micro and run of river hydro

- Applicable for areas with a dependable resource.
- Lower head systems available
- Run of river up to 50kW pre-commercial
- Generally larger infrastructure cost

Micro Hydro facility at remote ranch

UEK 50kW flow turbine

Hybrid System Power Converters

Trace Tech
100 kW
converter

Wales AK
156 kW rotary
converter

- Convert energy from DC to AC and back
- Some units contain power system control
- Solid state or rotary systems
- Solid state range in size from 1kW to 300kW
- Rotary systems built to size depending on needs
- Combined with batteries for storage

Batteries

- Many types
  - Lead Acid
  - NiCad
- Two uses/sizing:
  - Store energy to cover long periods
  - Store power to cover short periods
- Requires periodic replacement
- Sensitive to use and environment

Fly Wheels

- Combine the aspects of storage and a synchronous condenser
- Generally provide small amounts of storage
- Generally modular
- Spinning losses
- Long research history, very short operational experience

Dump Loads and Community Heating

- Remove excess energy from the grid
- Help to control frequency
- Made of resistive heating elements and some control
- Two uses
  - Dispatched to provide heating (excess wind)
  - Used as one aspect of the grid stability control (fast acting)

100 kW dump load

Synchronous Condensers

- Help to control voltage and balance active and reactive power needs on the grid
- Primarily used when all diesel engines have been shut off
- Made of a controlled AC generator running on the AC bus
- Consumes power as it rotates (losses)

75 kW Synchronous Condenser

System Controls

- The things that make everything work together.
- Individual components and central control
- High speed (behind the scene) and general control
- Can Reduce staffing costs and increase service

System Monitoring

Installation of system monitors allows plant operators to monitor system performance

- Allows economic evaluation
- With expert analysis system reduces maintenance and down time
- Small incremental cost
- Included in some converters and system controllers

Remote Access and Telecom

- Remote access allows oversight of system performance
- Enables real time system interrogation and troubleshooting even when off site
- Cell phone technology inexpensive with reasonable coverage

Satellite and cell phone communication equipment on remote power station

Key Issues of Large Hybrids

- Power Generation and Transmission
  - Penetration
  - Power Quality
- System Operation
  - Use of renewable energy when you have it
  - Issues of minimal loading on diesel engines
- System Maintenance
  - Level of system maintenance required

Issues of Power Generation and Transmission

- Power Quality of Systems
  - Variable renewable penetration of system
  - Power flow questions
  - Voltage variation on feeder lines
  - Level of technology/control existing in diesel plant

If at any time you are not producing enough power, power system will collapse

Complication with Uncontrolled Generation

Why are hybrids a complicated control question and need special attention in regards to power quality?

- By their nature renewables are stochastic (uncontrolled) and vary with the resource. The amount of variation and thus the amount required control depends on the renewable resource being used and the power system design
- Wind, river run hydro and solar technologies require adequate control to be productive

Types of Power Quality

- System stability - reliable power: Having power when you should have it.
  - Unscheduled blackouts
  - System failures
  - Voltage and frequency within acceptable limits
  - System power factor not overtaxing power system
- The level of harmonic distortion -is the power being delivered usable?
  - Changing structure of the power
  - Sub-cycle quality of the power

System Stability

Driven by maintaining system voltage, frequency and reactive power supply.

- **Voltage:** Currently uses an active controller on the diesel. Alternatives are a synchronous condensers or a battery bank and solid state or rotary power converter.
- **Frequency:** A balance of power supply and demand, controlled by the throttle of the diesel. Can be solved through the use of dump loads or power converters.
- **Power Factor:** Balancing active and reactive power as needed by the inductive motors and electronics on the system. Capacitor banks, motors or advanced solid state power converters.

Power Harmonics

- A matter of the type and quality of the electronic equipment employed in the design of the power systems.
- Requires fine tuning of the power system during installation, very dependent on equipment being used
- Should be insured as part of the testing and system commissioning
- Will required continued supervision and maintenance
- More impact on high tech or sensitive loads

PQ in Large Hybrid Systems

- Power generation primarily on the AC bus. Power quality is dependent on obtaining ways to control what is happening.
- Depends on
  - Configuration: Integrated solid state power power converter and controls, no storage with dump loads
  - Type and age of equipment: Diesel electronic and fuel controls
  - System integration: Overall system control
- Supply and demand side solutions to this problem

Supply Side Options

Options that affect only the power system as seen from the grid

- Dump Loads: Balance the generation and load - Can be automatic or controlled
- Synchronous Condenser: Provides reactive power and controls voltage.
- Advanced power converters and small battery bank: Used to assist in managing power flows, power smoothing.
- Active renewable control: Control power output of the renewable device.

Demand Side Options

Control options that can be completed on the grid side to support system power quality

- Distinction between critical and non critical loads
  - Dispatchable loads like resistance heating
  - Loads shedding where non-critical loads
  - Protection of sensitive loads
- Installation of capacitors to smooth out rapid system fluctuations and partially correct systems power factor.
- Replacing large inefficient loads

Active renewable control

Control of the offending power generation device to smooth out power output.

- Controlled shut down of renewable devices during high wind or low load periods
- Active power control of renewable technology.
  - Variable speed technology using power electronics
  - Active wind turbine control, variable pitch blades
- Resource smoothing using multiple units
  - smaller turbines spread out over a greater area
- Short and long term forecasting of system power

Wind Turbine Issues

- More smaller turbines are better than one large one
  - Smother power production
  - Higher impact of turbine reliability
  - but you do have space issues
- Turbine Size will likely be dictated by site conditions but smaller turbine (50-200 kW) will provide
  - Easier shipment and installation
  - Require smaller maintenance operations and facilities

System Operation

- **DC Based Power Systems** - very little operational oversight needed. One part time operator
- **Low penetration AC systems** - Can be operated as two independent power systems. Operators in full control of power system
- **Mid penetration AC systems** - Operators provide both maintenance and some control
- **High penetration AC systems** - Completely integrated control with little user interface required. System operators required to troubleshoot system problems but not to “operate” system.

Energy Storage

- Differences in Storage
  - Long term “energy” storage: Larger storage to hold energy from one time to another. Order of hours.
    - Batteries, compressed air, water/hydro, hydrogen
  - Short term “power” storage: Energy used for very short periods to provide grid stability and allow controlled diesel engine starting. On the order of minutes.
    - Batteries, fly wheels, ultra capacitors

General Battery Types

- Types:
  - Deep Cycle Batteries (traction or stationary batteries)
    - Robust construction designed for repeated, deep discharge
    - Highly suited (even optimized) for renewable energy storage
  - High Current Batteries
    - Batteries designed for high current applications, UPS and other short term storage

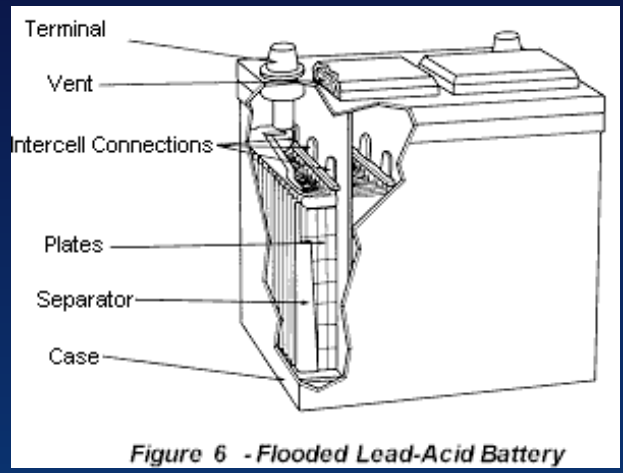


Figure 6 - Flooded Lead-Acid Battery

Types of Deep Cycle Batteries

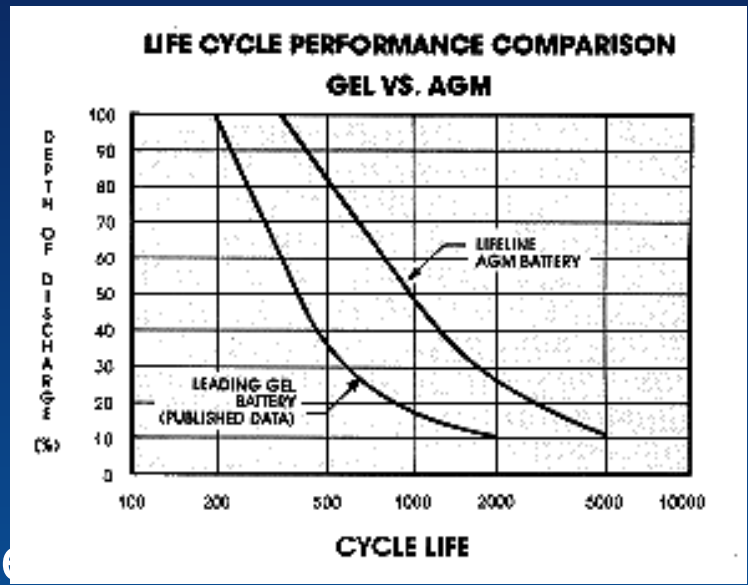
- Flooded Lead-Acid
  - Relatively inexpensive
  - Require maintenance
  - Fairly abuse tolerant (if kept watered and not too hot)
- VRLA (Valve-regulated Lead-Acid) or "Maintenance Free"
  - Comparable in cost to Flooded Lead-Acid
  - No maintenance (Really???)
  - Can be damaged by over-charging
  - Sensitive to temperature
- LA Gel Cells
  - Low maintenance but high cost
  - Good for residential use
  - Good reliability and life

High Current Batteries

- Ni-Cad
  - Excellent energy density
  - Long life
  - Low maintenance
  - Very expensive (10X the cost of Lead-Acid

Considerations for Batteries

- The deeper the discharge, the fewer the cycles
- One bad battery can bring down the whole string and can even affect parallel strings (practice due vigilance)
- Ensure a reliable supply of distilled water
- Avoid leaving batteries at a low state of charge for long periods
- Extractable capacity dependent on a number of factors and is usually not as large as expecte



Final Thoughts …

- Lots of options for the configuration of hybrid systems - Depend on load, resource, and costs.
- Medium penetration wind-diesel systems are operating in various isolated locations around the world. Instantaneous wind penetration levels exceeding 50% of load are common.
- Several high penetration systems, with and without energy storage, have been successfully demonstrated.
- High penetration systems are capable of prolonged diesel -off operation.

Conclusions

- Renewable based rural power systems can help supply energy to rural needs in a clean, inexpensive way that does not burden the national economy
- Renewable based rural power systems have many uses in the “non-traditional” sense
- Configuration depends on many factors
- Social issues dominate over technical issues

Renewable power systems have
a place in rural development